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THE ADAPTATION OF MULTI-WIRE PROPORTIONAL CHAMBERS WITH DELAY-LINE READOUTS FOR NEUTRON RADIOGRAPHIC IMAGING*

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Abstract

A proportional chamber employing delay-line readout has been adapted for thermal-neutron imaging through the use of a boron converter plate as one of the chamber electrodes. A small prototype chamber using natural B for a converter has achieved 0.5% thermal-neutron-detection efficiency and better than 2 mm resolution (10% - 90% knife-edge). A converter-plate-model calculation gives good agreement with the measurements and shows how efficiency and resolution vary with chamber thickness, energy discrimination, and B and Al-overcoating thicknesses. Substitution of ^{10}B for the natural B would give a five-fold increase in efficiency and the calculations indicate that a further improvement in both efficiency and resolution of up to 50% is achievable in a single-plate system. The results of these calculations and a comparison with measurements are presented.

Introduction

Neutron radiography has become an extremely valuable tool for non-destructive testing and present imaging techniques can produce very high resolution images, particularly with reactor neutron sources.[1] Where high resolution is not required but where high efficiency or contrast sensitivity are desirable, the optimum imaging characteristics could be provided by an efficient system, with reasonable resolution, that is sensitive to a single interaction and capable of digitizing its coordinates. Such a system could broaden the applications of low intensity, non-reactor, neutron sources such as ^{252}Cf and also make possible more extensive exploration of medical diagnostic applications of neutron radiography.[2]

Utilization of the $^{10}B(n, \alpha)^{7}Li$ reaction in conjunction with proportional counters is commonly employed as an efficient and highly selective technique for neutron detection. It was therefore a natural extension of the work of two of the present authors on multi-wire proportional chambers for low-dose X-radiography[3] to adapt a similar chamber for neutron radiography. This paper describes preliminary measurements and analysis made with a small prototype chamber.

Multi-Wire Proportional Chamber

Construction

The prototype chamber (Fig. 1) consists basically of three electrical planes with an active area of approximately 4.0 cm by 4.5 cm. The top plane is made up of twenty-three 0.005-inch-diameter gold-coated molybdenum wires spaced two mm apart. The center plane also contains twenty-three wires spaced two mm apart. The center seventeen wires are of 0.0008-inch-diameter gold-coated tungsten and the outside three wires on either side of the chamber are graduated in diameter with the extreme outside wires having a diameter of 0.010 inch. The gradual increase in wire diameter toward the outside of the plane is intended to minimize fringe field effects. The bottom plane is a solid aluminum plate with a 700 $\mu g/cm^2$ coating of natural boron and a 150 A overcoating of aluminum. Frames of Nema G-10 fiberglas epoxy were used as support structures for the wire planes and a third frame of the same material covered with thin mylar serves as a window. The wires of each plane are fastened at both ends by soldering to printed circuit boards. On one side of each plane the printed circuit strips are extended far enough to accept the delay line and then connected to a common strip through 220 kΩ resistors. The gas filling was a mixture of 90% argon and 10% methane.

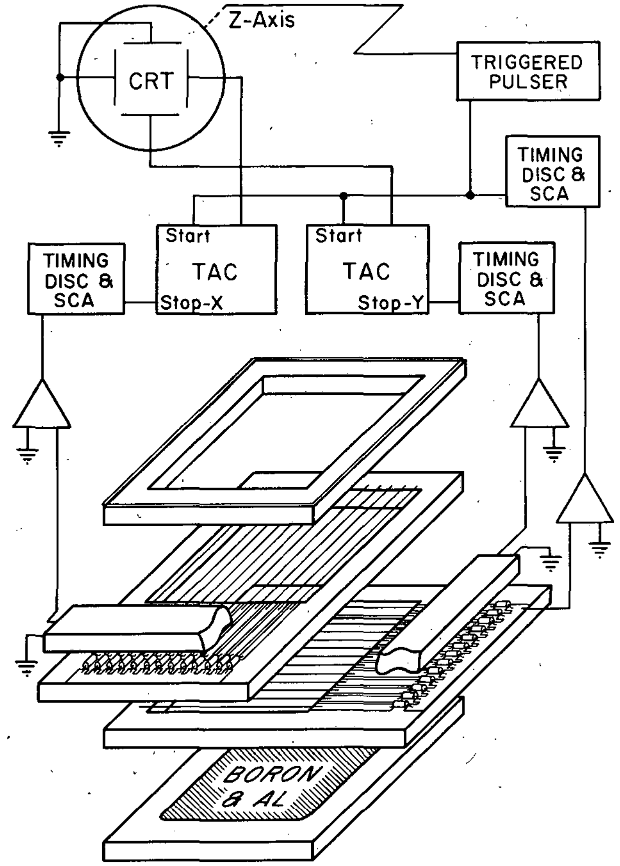

Fig. 1. Exploded view of wire chamber and delay lines with block diagram of imaging electronics.

Neutron Detection

Neutrons are incident on the top of the chamber and pass through the active volume of the chamber with essentially no interaction. When the neutrons reach the bottom plane some of them interact with the ^{10}B nuclei in the boron converter resulting in the emission of an alpha particle with an energy of approximately 1.5 MeV. If the interaction does not occur at too great a depth in the converter and if the direction of alpha emission is not too far from the converter normal, the alpha particle emerges into the active volume of the chamber and deposits its remaining energy in the gas in the form of ion-electron pairs. Since the central wire plane is at positive potential with respect to the converter plate and the top wire plane, the electrons will drift along field lines toward wires in the central plane. When the electrons reach a high field region very close to a wire, multiplication occurs and a negative pulse is produced on the wire. Simultaneously a positive pulse is induced on wires of the top plane by the initial motion of the ions away from the multiplication wire.

Image Readout

The voltage pulses on the wires are capacitively coupled from the printed circuit strips to the electromagnetic delay lines which lie directly over the strips. A pulse which is induced in the delay line is delayed by an amount proportional to the distance between the coupling point and the end of the line. A prompt reference signal is taken from the common strip of the central plane. Timing of the prompt and delayed signals is done using timing single channel analyzers (SCA). The x and y coordinates of an ionizing event are obtained by using the prompt timing pulse to start two time-to-amplitude converters and the delayed timing pulses to stop them. Either the x or the y analog pulses from the converters may be displayed on a pulse height analyzer for resolution studies. Alternatively, these pulses can be applied to the x and y deflection plates of a display oscilloscope producing spots of light that we then collect on Polaroid film to form the image.

If the projection of an alpha track on the central plane is of the order of a wire separation or less, then most of the electrons in the track will be attracted to a single wire. Hence, most of the pulses from the central plane appear to be centered on one of the multiplication wires. However, electron multiplication can occur anywhere along the length of a multiplication wire and positive pulses of varying amplitudes are induced on several of the closest cathode wires. When these pulses are coupled into the delay line a summing process occurs resulting in a single pulse with a center of gravity that corresponds closely to the location of the center of gravity of the ionization produced by the α-particle.

Sample x-ray and neutron images of 5/8-inch high stencil letters punched in 0.020 Cd and 0.016 in Pb are shown in Fig. 2. The distinct line pattern corresponds to multiplication wire spacing of 2 mm and is due to the pulse formation process.[4]

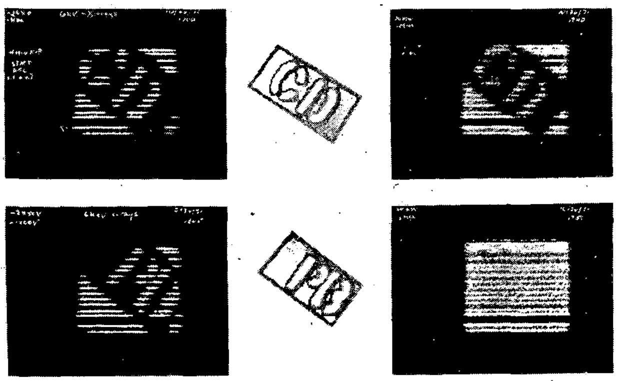

Fig. 2. Sample images of 5/8-in.-high stencil letters punched in 0.020-in. Cd and 0.016-in. Pb. The images on the left

were made with 6 keV X-rays from an ^{55}Fe source. Those on the right were made with the neutron radiography beam from the UCB reactor. The lead is transparent to the neutron beam. The source of the line structure in the image is described in the text. Irregularity in line spacing near the top of the images is mechanical in nature and due to irregularities either in the wire spacing or in the delay line. The large line gap at the bottom of the images is due to a missing wire.

In addition to the oscilloscope display of both planes for visual evaluation, quantitative resolution measurements have been made by reading out the cathode plane with a pulse-height analyzer. The PHA readout is convenient for actual resolution measurements since then the data is digitized for computer manipulation.

A simple resolution measurement was performed by placing a cleanly sheared sheet of cadmium over half of the chamber with the edge of the sheet aligned parallel to the cathode wires. Data was collected on the PHA. Sensitivity was not constant over the entire area of the chamber (cf. Fig. 2). Therefore this data was normalized, channel-by-channel, to data collected during a whole-chamber irradiation. Resolution was then taken to be the distance between 10% and 90% contrast values.

Measurements yielding more detailed information about system resolution were performed by replacing the single sheet of cadmium with a periodic array of cadmium strips. Four test plates with periods of 1.0, 0.6, 0.4, and 0.2 cm were made by gluing cadmium sheets to 0.125 inch aluminum backings and milling precision slots in the cadmium at equal intervals such that the strips were equal in width to the slots. The response to each test plate was then measured and normalized as described above for the solid sheet.

Detection efficiency was measured by placing a sheet of cadmium with a 0.500-inch-diameter hole in it in front of the chamber so only a small portion of the chamber where the sensitivity was reasonably constant would be illuminated. This procedure was adopted to eliminate edge effects which are significant in such a small chamber.

Results

The modulation transfer function (MTF) was calculated using the normalized data obtained from the cadmium strip test plates. The MTF is defined in terms of system response to sinusoidal spatial variations in a parallel beam (the angular divergence of our beam was negligibly small, 0.25°, over the range of measurements). Cadmium strips cause a step change in neutron intensity creating a square wave object function. So to calculate a point of the MTF we Fourier analyzed both the square wave object function and the chamber's response (image function) for the amplitude of the first harmonic at each of the four test plate frequencies.

The contrast ratio is the ratio of the fundamental amplitude of the image function to the fundamental amplitude of the object function. The solid curve of Figure 3 is a plot of these results.[5] The 10% to 90% width was measured under the same conditions as the MTF and was observed to be about 0.20 cm.

Based on gold-foil measurements of neutron flux, efficiences as high as 0.5% have been obtained. This value is lower than the calculated maximum efficiency of 1.18% due in part to a low-energy detection threshold and in part to the fact that the boron layer was under optimum thickness. Since the abundance of ^{10}B in natural boron is only 20%, the efficiency can be increased by a factor of five through the use of a highly enriched ^{10}B converter.

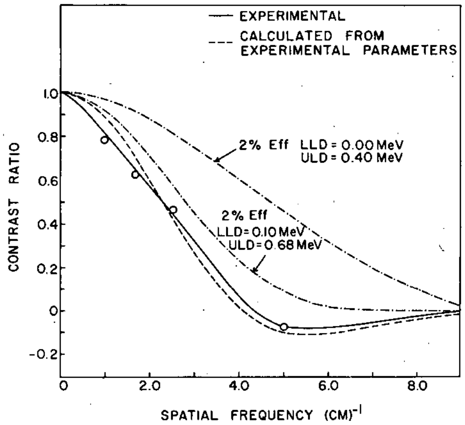

Fig. 3. Experimental and calculated contrast ratios vs. spatial frequency, modulation transfer functions (MTF). The experimental energy discrimination parameters were estimated to be 0.35 MeV (LLD) and 0.65 MeV (ULD). These are the values used in the comparison calculation. Under these conditions a phase inversion is calculated for the higher spatial frequencies. Since no phase information was obtained experimentally, the choice of sign for the experimental point at 5 cycles/cm was based on the calculation.

Computer Analysis

The total MTF of an imaging system is the product of the MTF's for each process that is involved in producing the image. In our system these processes include the following:

1. Neutron transmission through the object being radiographed
2. The n-α conversion
3. Localization of an event by the chamber

4. Delay line readout

5. Electronic signal processing

The value of the MTF for an individual process sets an upper limit on the value of the total MTF.

A computer program has been developed to model the n-α conversion process by calculating the spatial distribution of alphas due to a parallel beam of neutrons. The program proceeds by first calculating emission of alphas from finite differenced layers in the converter into finite differenced solid angles in the chamber. The residual range of the alpha[6] as it leaves the converter is then calculated for the particular converter depth and solid angle of emission. The energy corresponding to this residual range is checked to see if it lies between two energy values set at the beginning of the problem (discriminator settings of the SCA's, called LLD and ULD). Next, the track length in the gas of the chamber is calculated and a point is chosen on the track such that the alpha deposits half of its energy on either side. Finally, the vector joining this point and the point at which the alpha entered the chamber is projected onto the wire planes and is taken to be the effective x-y location of the ionizing event.

Each locus in Figure 4 is the set of points where alphas from a particular depth in the converter will stop. The numbers which appear on alternate curves are the percent of total alpha yield contributed by alphas that stop on the curve. Alpha track lengths in the gas are shorter for alphas which come from deeper portions of the converter. Past a depth of about 5 μm further emission is not possible. Although these curves were calculated for a ^{10}B converter they apply also to natural boron except for slightly different (0-4%) relative yields from the various layers due to decreased self-shielding in natural boron. The two circular segments drawn on Figure 4 are curves of constant energy and correspond to alpha energy depositions of 0.1 and 1.0 MeV.

If the response of the chamber is truly proportional or at least monotonically related to the amount of energy deposition, then the circular segments correspond to energy cutoffs that can be set on the SCA's. The α's which then contribute to image formation are those with stopping points which lie between the circular segments. A stopping-point plot for a thin converter would be similar to Figure 4 except that some of the inner loci would be missing. Outer loci can be eliminated by coating the surface of the converter with a thin layer of non-converting material such as aluminum. Varying chamber thickness has the effect of flattening longitudinally all curves corresponding to an α range greater than the chamber thickness. The effects of aluminum overcoat, window width, and chamber thickness on efficiency are shown in Figures 5 and 6. After the distribution of effective event locations is found it is used in performing the convolution integrals which yield the 10% to 90% knife-edge resolution and the contrast ratios for the MTF. Resolution results are also shown in Figures 5 and 6. The dashed curves of Figure 3 are MTF's calculated by the program.

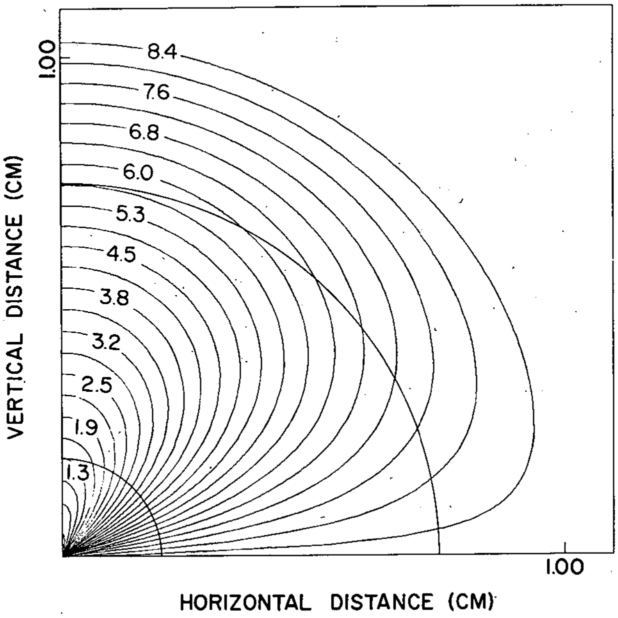

Fig. 4. Locus plot showing α-particle track endings for 1.5 MeV α particles originating at various depths in the converter.

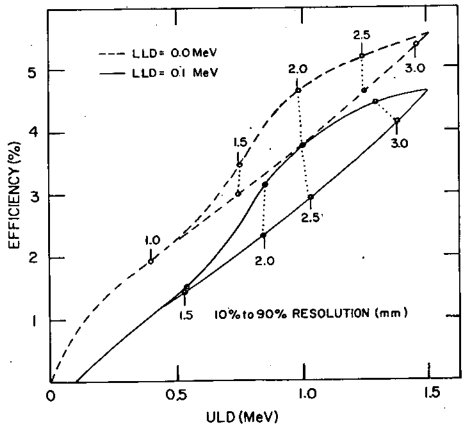

Fig. 5. Calculated efficiency and resolution vs. α-energy-acceptance window for a thick, uncoated ^{10}B conversion screen. The window limits are defined by the settings of an upper-level discriminator (ULD) and a lower-level discriminator (LLD). The upper and lower branches of each curve correspond to sensitive chamber thicknesses of 0.4 and 1.0 cm respectively.

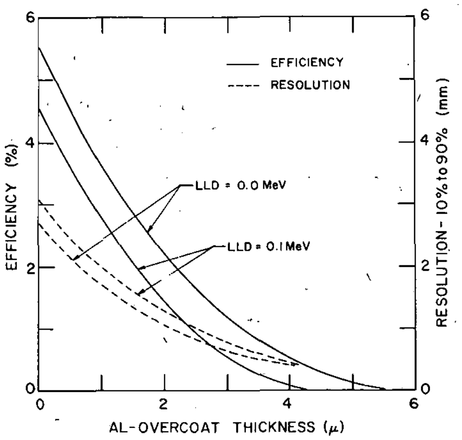

Fig. 6. Calculated efficiency and resolution vs. thickness of an Al overcoat on a thick ^{10}B converter. The curve labeled LLD = 0.0 MeV includes all α's reaching the chamber. The curve labeled LLD = 0.1 MeV includes only those α's that deposit at least 0.1 MeV in the chamber.

Conclusions

Using present construction methods the resolution of a wire chamber is limited in at least one dimension by the wire spacing. This places a practical upper limit on the resolving capability that need be obtained from the n-α process. Chambers with 24 wires per inch have been successfully operated and chambers with 48 wires per inch are planned.[3] Computer results indicate that the resolving capability of the n-α process can be made compatible with wire spacings as fine as 48 per inch, but at the expense of a large decrease in efficiency. However, by proper choice of design parameters such as chamber thickness and overcoat thickness and possibly by using a denser gas such as xenon for the chamber filling, resolution of the order of a mm or less should be obtainable at an efficiency of 3% – 4% with a single ^{10}B converter. This efficiency can then be doubled by placing a ^{10}B converter on both sides of the chamber.

Acknowledgements

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